Subdivision curves and surfaces

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Subdivision curves

Idea:
- repeatedly refine the control polygon
  \[ P_1 \to P_3 \to P_5 \to \cdots \]
- curve is the limit of an infinite process
  \[ Q = \lim_{n \to \infty} P_n \]

Chaikin’s algorithm

Chaikin introduced the following “corner-cutting” scheme in 1974:
- Start with a piecewise linear curve
- Insert new vertices at the midpoints (the splitting step)
- Average each vertex with the “next” (clockwise) neighbor (the averaging step)
- Go to the splitting step

Reading

Required:

Note: there is an error in Stollnitz, et al., section A.5. Equation A.3 should read:
\[ MV = VA \]
This is already fixed in the handout.
Averaging masks

The limit curve is a quadratic B-spline!

Instead of averaging with the nearest neighbor, we can generalize by applying an averaging mask during the averaging step:

\[ a = (\ldots, a_i, a_{i+1}, a_{i+2}, \ldots) \]

In the case of Chaikin’s algorithm:

\[ a = \left( \frac{1}{4}, \frac{1}{2}, \frac{1}{4} \right) \]

Different averaging masks lead to different curves.

For example,

\[ a = \left( \frac{1}{4}, \frac{1}{2}, \frac{1}{4} \right) \]

Leads to **cubic** B-spline curves.

Limit curves and evaluation masks

Can we push a curve to the limit position in one step? Yes!!

We can stop after a number of split-average steps and apply an evaluation mask to push the vertices onto the limit curve.

For Chaikin’s algorithm, the evaluation masks is:

\[ e = \begin{bmatrix} 0 & \frac{1}{2} & \frac{1}{2} \end{bmatrix} \]

For cubic subdivision, the evaluation masks is:

\[ e = \begin{bmatrix} \frac{1}{6} & \frac{2}{3} & \frac{1}{6} \end{bmatrix} \]

Building complex models

We can extend the idea of subdivision from curves to surfaces…

Subdivision surfaces

Chaikin’s use of subdivision for curves inspired similar techniques for subdivision surfaces.

Iteratively refine a **control polyhedron** (or **control mesh**) to produce the limit surface

\[ S = \lim_{j \to \infty} P_j \]

using splitting and averaging steps.
**Triangular subdivision**

There are a variety of ways to subdivide a polygon mesh.

A common choice for triangle meshes is 4:1 subdivision – each triangular face is split into four smaller triangles:

![Original and After splitting](image)

**Loop averaging step**

Once again we can use masks for the averaging step:

- **Vertex neighborhood**
- **Averaging mask** (before affine normalization)

\[ Q \leftarrow \frac{\alpha(n)Q_1 + \cdots + Q_n}{\alpha(n) + n} \]

where

\[ \alpha(n) = \frac{n(1 - \beta(n))}{\beta(n)} \quad \beta(n) = \frac{5}{4} \left(3 + 2\cos(2\pi/n)\right)^2 \]

These values, due to Charles Loop, are carefully chosen to ensure smoothness – namely, tangent plane or normal continuity.

Note: tangent plane continuity is also known as \(G^1\) continuity for surfaces.

**Recipe for subdivision surfaces**

As with subdivision curves, we can now describe a recipe for creating and rendering subdivision surfaces:

- Subdivide (split+average) the control polyhedron a few times. Use the averaging mask.
- Compute two tangent vectors using the tangent masks.
- Compute the normal from the tangent vectors.
- Push the resulting points to the limit positions. Use the evaluation mask.
- Render!

**Loop evaluation and tangent masks**

As with subdivision curves, we can split and average a number of times and then push the points to their limit positions.

- **Evaluation mask**
- **Tangent masks**

\[
\bar{Q}^n = \frac{\alpha(n)Q_1 + \cdots + Q_n}{\alpha(n) + n}
\]

\[
\bar{T}_1^n = \tau_1(n)Q_1 + \cdots + \tau_n(n)Q_n
\]

\[
\bar{T}_2^n = \tau_2(n)Q_1 + \cdots + \tau_n(n)Q_n
\]

where

\[
\alpha(n) = \frac{3n}{\beta(n)} \\
\tau_i(n) = \cos(2\pi i / n)
\]

How do we compute the normal?

\[ \vec{N} \sim \vec{T}_1^n \times \vec{T}_2^n \]
Adding creases without trim curves

For NURBS surfaces, adding sharp features like creases required the use of trim curves.

For subdivision surfaces, we can just modify the subdivision masks. E.g., we can mark some edges and vertices as "creases" and modify the subdivision mask for them (and their children):

This gives rise to $G^0$ continuous surfaces (i.e., having positional but not tangent plane continuity).

Catmull-Clark subdivision

4:1 subdivision of triangles is sometimes called a face scheme for subdivision, as each face begets more faces.

An alternative face scheme starts with arbitrary polygon meshes and inserts vertices along edges and at face centroids:

Catmull-Clark subdivision:

Note: after the first subdivision, all polygons are quadrilaterals in this scheme.

Summary

What to take home:

- The meanings of all the **boldfaced** terms.
- How to perform the splitting and averaging steps on subdivision curves.
- How to perform mesh splitting steps for subdivision surfaces, especially Loop.
- How to construct and render subdivision surfaces from their averaging masks, evaluation masks, and tangent masks.